Emergent Short–Range and Long–Range Attractive Forces from Particle Collisions in a Gas of Indivisible Particles

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Abstract

We propose a kinetic–theory framework in which a gas of indivisible, finite–volume particles—each possessing translational and rotational degrees of freedom—exhibits emergent attractive forces arising solely from collisional dynamics. By incorporating a sliding interaction that partially converts tangential translational momentum into rotation during collisions, local gradients in effective temperature and pressure are generated. These gradients produce effective attractive forces on two scales: (i) a short–range attraction resulting from localized energy dissipation during collisions, and (ii) a long–range, thermophoretic–like attraction arising from spatially extended energy gradients. This model suggests that field–free, collisional processes can lead to emergent binding effects in many–body systems.

1 Introduction

Traditionally, attractive forces are attributed to field–mediated interactions (e.g., gravitational or electromagnetic forces). In this work, we examine an alternative: effective attractions emerging purely from collisional processes in a gas of particles that are both finite in volume and indivisible. In our model, each particle has translational and rotational degrees of freedom, and collisions include a *sliding* component that channels a fraction of the tangential momentum into rotation. The resulting energy redistribution creates local inhomogeneities in the translational kinetic energy, which can be interpreted as effective potential wells and pressure gradients, thereby driving attractive interactions over both short and long ranges.

2 Model and Assumptions

2.1 Particle Properties

- **Indivisible and Finite Volume:** Particles are treated as fundamental entities with a fixed volume and no substructure.

- **Degrees of Freedom:** Each particle has three translational degrees of freedom. In addition, they possess r rotational degrees of freedom (e.g., $r = 3$ for a full 3D rigid body, or fewer if symmetry applies). Vibrational modes are absent.

2.2 Collision Dynamics

- **Sliding Interaction:** During a collision, a fraction α of the tangential component of the relative velocity is transferred into rotation. Consequently, the fraction of tangential kinetic energy converted is given by

$$F = 1 - (1 - \alpha)^2.$$

  For example, $\alpha = 0.3$ yields $F \approx 0.51$, approaching equipartition between translation and rotation.

- **Energy Redistribution:** In the absence of sliding ($\alpha = 0$), collisions preserve a Maxwell–Boltzmann distribution in translation. With sliding, energy partitions between translation and rotation, resulting in effective temperatures T_{lin} and T_{rot}, which are approximately related by

$$\frac{T_{\text{rot}}}{T_{\text{lin}}} \sim \frac{F}{1 - F}.$$

3 Emergent Short–Range Attractive Forces

At the scale of individual collisions:

- **Local Energy Dissipation:** When two particles collide, the sliding interaction transfers a fraction of their tangential kinetic energy into rotation. This localized loss of translational energy effectively lowers the local "temperature" (i.e., average kinetic energy) in the collision region.

- **Effective Potential Well:** The reduction in translational energy leads to a locally lower pressure, given by

$$P = nkT_{\text{lin}},$$

  where n is the particle number density and k is Boltzmann's constant. This local pressure dip can be interpreted as an effective potential well that draws nearby particles together. Formally, an effective potential $U_{\text{eff}}(r)$ can be defined via

$$U_{\text{eff}}(r) \propto -\int \frac{dP}{dr}\, dr.$$

Thus, collisions themselves generate an effective short–range attraction without requiring an intrinsic binding force.

4 Emergent Long–Range Attractive Forces

In an extended system with spatial variation in collisional properties:

- **Spatially Varying Coupling:** Consider a region where high–coupling particles (with large α) are concentrated, causing strong local energy dissipation, versus regions dominated by low–coupling particles. The high–coupling region will exhibit a lower effective translational temperature.
- **Temperature and Pressure Gradients:** Energy transport via collisions establishes a steady–state temperature profile. For instance, in spherical symmetry, assume a "cool" core of radius R at temperature $T_{\rm surf}$ and a far–field temperature T_0. A simple radial profile may be approximated as

$$T_{\rm lin}(r) = T_{\rm surf} + (T_0 - T_{\rm surf})\frac{R}{r} \quad (r \geq R).$$

  The corresponding pressure gradient,

$$\frac{dP}{dr} = nk\frac{dT_{\rm lin}}{dr},$$

  produces a net force.
- **Thermophoretic Force:** Analogous to thermophoresis, a particle in a temperature gradient experiences a net force from the momentum flux of collisions. This force drives particles toward regions of lower translational energy (and pressure), effectively generating a long–range attractive interaction.

5 Discussion

Our analysis indicates that collisional dynamics alone can induce effective attractions:

- **Short Range:** Local energy dissipation during collisions creates potential wells that bind particles at short distances.
- **Long Range:** Spatial variations in effective collisional coupling set up extended temperature and pressure gradients. The resulting thermophoretic–like forces attract particles over distances much larger than the individual particle size.

This mechanism shows that emergent forces need not be introduced as fundamental interactions; rather, they may be a macroscopic consequence of underlying non–equilibrium, many–body collisional processes.

6 Conclusion

We have developed a kinetic–theory model demonstrating that a gas of indivisible, finite–volume particles—subject to sliding interactions during collisions—can exhibit emergent attractive forces without invoking intrinsic field–mediated binding. Collisional energy redistribution generates local drops in translational energy that produce effective short–range potential wells. Additionally, spatial gradients in effective temperature and pressure yield long–range, thermophoretic–like forces that draw particles together. This work offers a novel perspective on how many–body dynamics can give rise to effective interactions solely from collisional processes.